










## Investigating the Effect of Trivalent Chromium Cr(III) Contamination on Geotechnical Properties of Clayey Soil

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### Abstract

Industrial wastes in the form of chromium, generated by leather industries, commonly contaminate soil, affecting its geotechnical properties. The present study examines the impact of trivalent chromium Cr(III) on the soil's mechanical, physiochemical, and microstructural properties. The soil and Cr(III) were collected from an industrial area in Sheikhpura, Pakistan, and are mixed in various proportions ranging from 0% to 50% by weight to simulate various contamination levels. A detailed experimental program that included index and strength testing, in addition to physiochemical analysis, was carried out. Modifications in microstructure and mineralogical composition were also examined using Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD). The results showed an increase in the soil strength characteristics, with maximum dry density (MDD) and cohesion enhanced up to 15% and 12%, respectively, with an addition of Cr(III) up to 20% contamination concentration. Notable reduction in the soil pH was also observed, indicating the acidic impact of Cr(III). Microstructural examination affirmed significant mineralogical rearrangement, with quartz remaining the dominant mineral. The results provided useful insights into the geotechnical implications of Cr(III) contamination in clayey soils and will contribute to improved assessment of the soil behavior in industrially contaminated zones.

**Keywords:** Trivalent Chromium Cr(III); X-Ray Diffraction (XRD); SEM; Cohesion; Angle of Internal Friction.

## 1. Introduction

The rapid increase in urbanization has resulted in fast-track societal development across many developing nations. Furthermore, this growth has also amplified environmental challenges with regard to industrial waste disposal and soil contamination. The functioning of the leather tanning industry results in considerable heavy metal pollution, particularly chromium contamination [1, 2]. The leather processing required extensive utilization of chromium salts due to their advantages of providing higher resilience, flexibility, and resistance in the finished product. However, a notable amount

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of chromium compounds remained unused, which are then discharged as industrial waste, in surrounding soil and water bodies, posing notable geotechnical concerns in addition to the ecological problems [3]. The contamination becomes more problematic in the regions where untreated wastes penetrate deeper in the ground, altering the soil structure and the corresponding strength characteristics [4].

In general, chromium prevails in two stable oxidation states: (i) Trivalent chromium, Cr(III), and (ii) Hexavalent chromium Cr(VI) [5]. Out of these two, Cr(VI) is considered more toxic and mobile because of its high solubility and strong oxidation potential. Hence, the environmental impacts of Cr(VI) and its remediation have been the domain of interest for researchers in the past few decades [6, 7]. Recent studies have revealed that employing remediation techniques considering nanomaterials, biochar amendments, and microbial treatments reduced ecological risks [8].

Heavy metal contamination has important implications for soil engineering, in addition to environmental concerns, as higher contamination may impact physical, chemical, and mechanical properties of the soil [7]. Liquid waste materials mixed in soil in higher concentrations affect the soil moisture characteristics, compaction, hydraulic conductivity, and shear strength characteristics [2, 9, 10]. The changes in the key engineering parameters are attributed to physiochemical interactions between contaminants and soil particles, including mineralogical and structural changes in the soil, alterations in thickness of electric double layer and ion exchange, etc. Research studies have also concluded that soil contamination significantly reduces the shear strength, which initiates soil stability problems and poses risks to infrastructure constructed on the contaminated ground [11-15].

To further improve understanding of these effects, advanced analytical techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and microstructural imaging methods were employed by the researchers. The aforementioned techniques allow the researchers to assess the soil-contaminant interaction at the microscopic level and to highlight structural changes, which govern the variation in soil index and characteristics. The research studies employing advanced analytical techniques confirmed that significant soil contamination can alter the soil pore structure and particles' bonding and structure, which ultimately impact the soil strength and deformation response [16-18].

Regardless of intensive research work on heavy metal contamination, there are few limitations in the current literature. The first is that most of the research studies were primarily focused on the environmental and remediation aspects of chromium contamination instead of evaluating its impact on the geotechnical characteristics of the soil. The second important limitation is that the majority of the research studies involved soil contamination by hexavalent chromium, Cr(VI), due to its toxicity, while nominal attention has been given to trivalent chromium, Cr(III) [19-24]. Another noteworthy gap in the literature is nominal studies integrating traditional soil testing with a comprehensive microstructural and mineralogical analysis to enhance understanding of the behavior of chromium-contaminated soils [25-27]. Adopting this integrated approach is vital to investigate the suitability of the soils contaminated with industrial wastes for construction purposes. This combined approach is essential in developing countries where industrial wastes are repeatedly disposed of near infrastructural development regions.

Consequently, the present work aims to examine the impact of trivalent chromium Cr(III) contamination on the geotechnical and microstructural properties of fine-grained clayey soil collected from the industrial area in Pakistan. The soil samples were mixed with varying concentrations of Cr(III) to imitate altering levels of contamination. A comprehensive laboratory testing program was implemented that includes particle size analysis, Atterberg's limits test, compaction tests, unconsolidated, undrained triaxial tests, and physiochemical analysis using a pH test. Furthermore, scanning electron microscopy (SEM) and X-ray diffraction (XRD) tests were performed to carry out microstructural and mineralogical analyses. Using this systematic approach, the research study yielded new insights into the mechanical response of chromium-contaminated soil and refined the assessment of the stability of the soil in industrially affected regions. The results of the present study will assist practicing geotechnical engineers to enhance their understanding of the mechanical behavior of soil contaminated with Cr(III) to design reliable and sustainable construction policies and methods for contaminated regions.

## 2. Research Methodology

The methodology adopted for the present study included the collection of soil and trivalent chromium from a suitable industrial region, followed by mixing them in varying proportions to cover various levels of contamination. Index and strength testing are then performed on the aforementioned contaminated samples to examine the impact of contamination on geotechnical properties, in addition to scanning electron microscopy (SEM) and X-ray diffraction (XRD) tests, which are performed to investigate microstructural and mineralogical properties. Various steps involved in the methodology are presented in Figure 1.

The methodology of the present study is formulated on the basis of the assumption that strength characteristics of the fine-grained soil, such as clay, are primarily controlled by interparticle forces, the soil fabrics, and structure. Notable alterations may result in these parameters from the introduction of contaminants such as trivalent chromium, Cr(III). The most commonly used failure criterion in the field of soil mechanics is Mohr-Coulomb's criterion, which defines the

shear strength of the soil as a function of cohesion and frictional angle. The modification in the soil structure or bonding between particles will impact these parameters. The addition of Cr(III) ions impacts the clay double layer, leading to alterations in interparticle attraction. The study in hand examines the impact of Cr(III) contamination on the soil by using a systematic approach, which involves assessment of impact not only on the strength characteristics of the soil but also on physiochemical and microstructural behavior. This integrated approach will enhance an understanding of the mechanism of Cr(III) affecting the soil geotechnical characteristics.

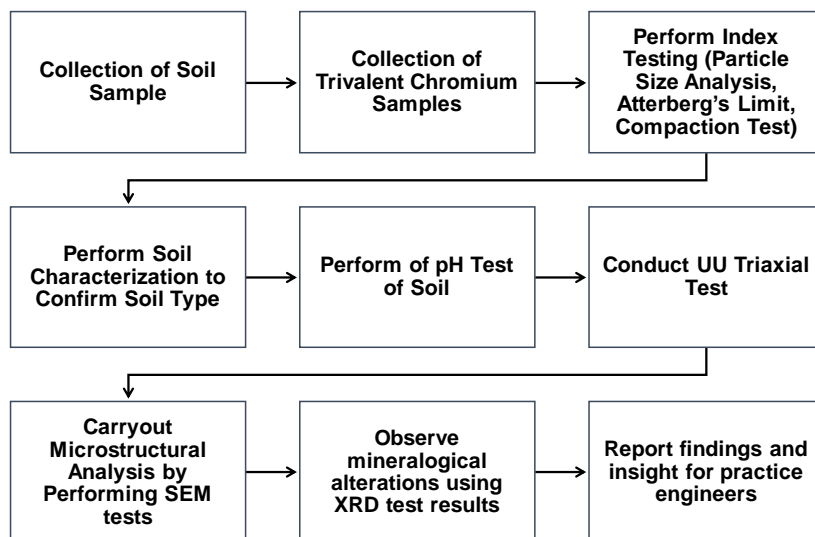


Figure 1. Flowchart of the research methodology

### 2.1. Soil and Trivalent Chromium Cr(III) Collection

The soil samples were collected from the Royal Leather Industries, located at Lahore- Sargodha Road, Sheikhpura, using an open pit excavation method following guidelines prescribed by ASTM standards. The site lies in an industrial city located approximately 38 km northwest of Lahore, the second-largest city of Pakistan. The geographic coordinates of the site are 31041'03" N and 74001'57" E, respectively. The area is a part of Rachna Doab, comprised of sediments transported by the channel from the Chenab River. The old basins occupy clay materials likely from the Pleistocene age, derived from the combination of sedimentary and metamorphic rocks of the lower Himalayas. Dark brown, cohesive soil was observed during the soil collection. The collected soil was carefully preserved and later transported to the Soil Fertility Research Institute, Lahore, for testing. The soil and trivalent chromium Cr(III) properties are presented in Tables 1 and 2.

Table 1. Soil Properties

Color	Dark Brown
Liquid Limit (%)	24.7
Plastic Limit (%)	19.16
Plastic Index (%)	5.54
pH	8.2
Density (kg/m <sup>3</sup> )	1687.98
Natural Moisture Content (%)	3.43
Specific Gravity	2.8
Classification	Silty Clay (USCS); A-2-4, (AASHTO)
Cohesion (kPa)	191.23

Table 2. Properties of Trivalent Chromium Cr(III)

Color	Greyish
pH	3.5
Density (kg/m <sup>3</sup> )	5220
Specific Gravity	7.5
Classification	Cr(III) in powder form

The collected soil sample and the performance of wet sieving are shown in Figure 2. The particle size distribution curve, as shown in Figure 3, showed around 76.7% of the soil passed through sieve no. 200, indicating fine-grained soil. The results of particle size analysis and Atterberg’s limits revealed the soil as Silty Clay (CL-ML) as per USCS, whereas it belonged to group A-2-4 as per the AASHTO soil classification system.

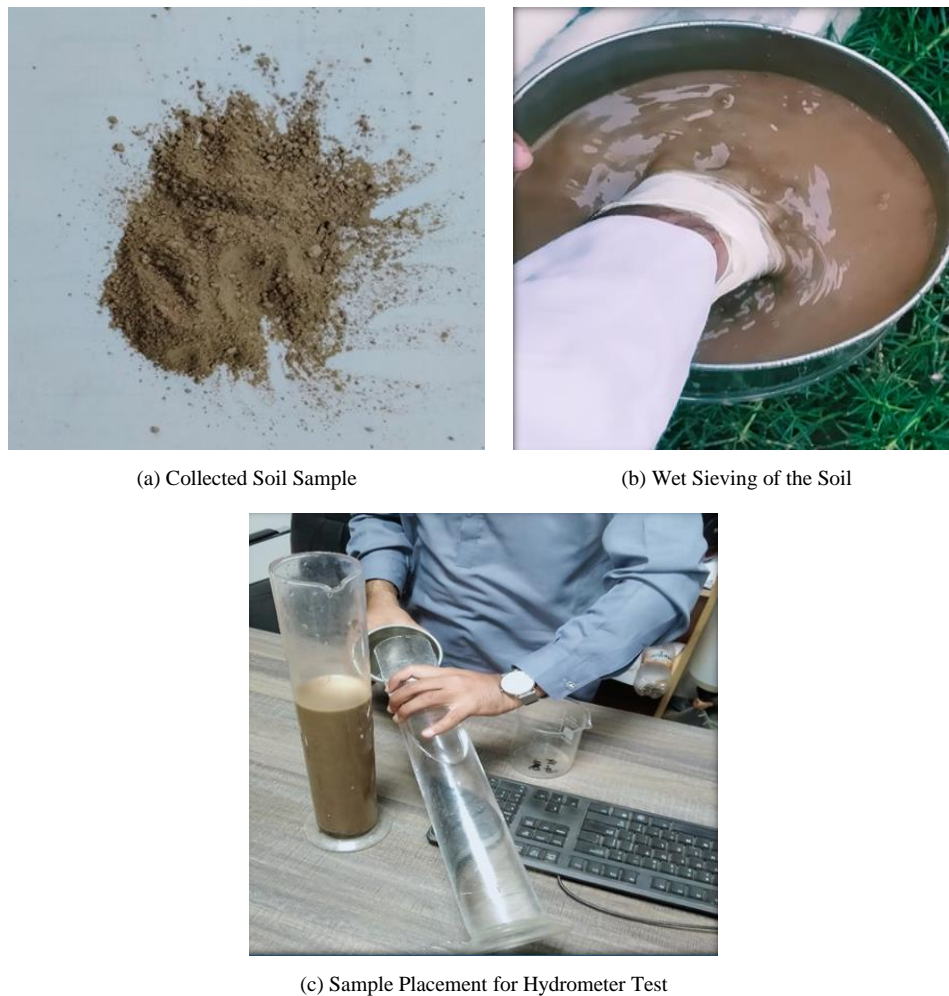


Figure 2. Particle Size Analysis (a) Collected Soil Sample (b) Wet Sieving (c) Sample Placement for Hydrometer Test

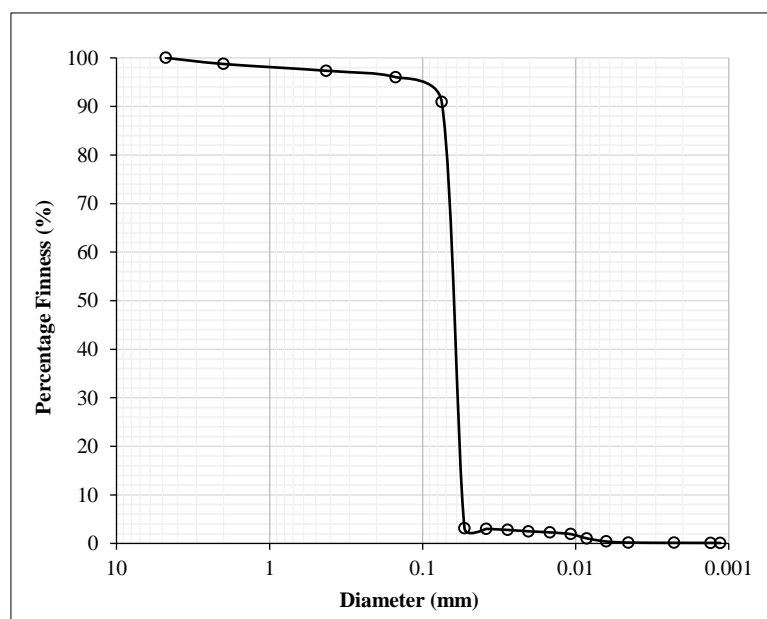


Figure 3. Particle Size Analysis of Pure Soil

## 2.2. Soil Sample Preparation

Oven-dried soil samples were prepared by adding Cr(III) in different percentages by the dry weight of the soil. The oven-dried soil was mixed with powder Cr(III) manually using hand mixing. The oven-dried sample, passed through sieve no. 40, was first weighed using a digital balance with 0.01 g accuracy. The calculated weight of Cr(III) was then added gradually to the soil and mixed using a stainless steel spatula in a large mixing tray for a minimum of 10 minutes per sample to ensure a homogenous mixture. The uniformity was ensured by implementing a quality control protocol. Homogeneity and uniformity were assessed through consistent visual appearance. Additionally, replicate samples were also prepared for some tested conditions. A total of nine (09) percentages, including 0%, 2.5%, 5%, 7.5%, 10%, 20%, 30%, 40%, and 50% according to the dry weight of the soil, were used. The mixing ratios of Cr(III) (ranging from 0% to 50%) represented a broad spectrum of contamination scenarios, from minimal to severe, reflecting the varying degrees of industrial waste exposure in real-world situations. These ratios allow for a comprehensive assessment of the progressive impact of Cr(III) on the geotechnical properties of clayey soil. Three (03) remolded samples for each percentage were prepared and tested instantaneously, as the present study is focused on the short-term/instant effect of Cr(III) contamination on geotechnical characteristics of the soil. This practice aligns with previously published research studies to investigate the effect of contaminants on the strength characteristics of the soil [9, 12].

## 2.3. Experimental Program

A series of experiments, including index, strength, SEM, and XRD tests, was performed to fulfill the objectives of the present study. The index properties were studied by performing three tests: (i) Particle size analysis; (ii) Atterberg's limit test; and (iii) Modified proctor tests, following ASTM D6319/D6913M, ASTM D4318, and ASTM D1557 standards, respectively. Using the results of the index tests, the soil was classified using Unified Soil Classification Systems (USCS) and the American Association of State Highways and Transportation Officials (AASHTO) classification systems, following the guidelines prescribed in ASTM D2487.

The soil engineering characteristics were evaluated by performing triaxial tests. Unconsolidated Undrained (UU) tests were performed in accordance with ASTM D2850, and the values of cohesion and angle of internal friction were obtained. The standard triaxial test system employed in this study was developed by Wykeham Farrance, a soil mechanics division of CONTROLS S.R.L., Italy. The system consists of a TRITECH 50kN-100kN, a high-performance load frame, and a standard triaxial cell capable of performing tests on samples ranging from 35 mm to 100 mm in diameter. Additionally, the system is equipped with a hydromatic standalone pressure/volume controller, water pressure source, and volume change controller for applying cell and back pressure. GEODATALOG, a data acquisition unit connected to the equipment, is attached for automatic data transfer in real-time for live plotting and monitoring of the tests in progress. The maximum sampling rate of the system is 500 readings per second.

The effect of Cr(III) on the physiochemical properties of the soil was studied by determining the pH value of the soil through a digital pH meter, X-ray diffraction tests (XRD), and scanning electron microscopy (SEM) tests. XRD tests were performed to identify various minerals in the soil sample. The diffraction of the test rays produced the relative peaks at specific angles. The identification of the minerals was then performed in the next stage. An XRD test was conducted using D2PHASER, which is a desktop diffractometer for all X-ray powder diffraction applications. The salient features of the equipment include a usable angular range of 3-1600 2 Theta, accuracy up to 0.02 degrees throughout the entire measuring range, an achievable peak width of less than 0.05 degrees, and X-ray generation of 30kV/10mA. DIFFRAC.SUITE software was employed for qualitative and quantitative phase analysis. Scanning electron microscopy (SEM) tests were carried out to analyze the microscopic structure along with the mineralogy of the soil. FEI NOVA 450 Nanosem scanning electron microscope with 1 nm ultimate resolution was employed for the present study. The detailed procedures of these tests are well documented in the literature [28].

## 3. Results and Discussion

### 3.1. Effect on Atterberg's Limits and Plasticity Index

The variation of liquid limit, plastic limit, and plasticity index with varying percentages of Cr(III) is presented in Figure 4. The results indicated the liquid limit, plasticity limit, and plasticity index increased up to 10% of Cr(III) addition and decreased afterwards. The primary reason for the increase in liquid and plastic limits was attributed to the water absorption of Cr(III). The exchangeable cations significantly affected clay plasticity, ultimately enhancing the collapse potential of the soil. This finding is consistent with the conclusions drawn by Terzaghi et al. [29]. The plastic limits increased due to the increased hydration energies of divalent cations, leading

to an increase in swelling potential and collapsibility of the soil, as documented by Gibbs & Bara [30]. The addition of a significant amount of Cr(III) decreased the soil properties, resulting in the transition of the soil state. The obtained trends of variation of Atterberg's limits and plasticity index with Cr(III) concentration align with the already published results [21].

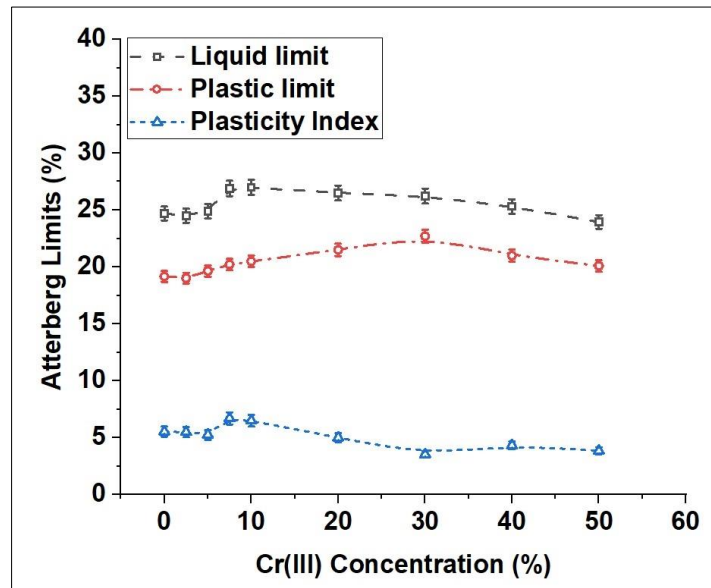


Figure 4. Variation of Atterberg's limit with Cr(III) Concentration

### 3.2. Effect on Maximum Dry Density (MDD) and Optimum Moisture Content (OMC)

The variation of Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) with percentages of Cr(III) is presented in Figures 5 and 6, respectively. The results showed that the maximum dry density increased up to a 20% addition of Cr(III) and remained almost constant afterwards. This increase in the MDD up to 20% addition was primarily because of the re-arrangement of clayey soil and higher density of Cr(III) (51.91 kN/m<sup>3</sup>), significantly higher than the soil. When it was mixed with the soil, the density of the contaminated soil increased. The increase in maximum dry density (MDD) observed up to 20% Cr(III) addition is in contrast with studies on Cr(VI) contamination, where these properties generally decreased linearly with increased contaminant levels [2]. The distinctive behaviour observed in the present study is attributed to the unique interaction between Cr(III) and the clay minerals. This interaction causes an initial re-arrangement and densification of soil particles, unlike the dispersive effect of Cr(VI).

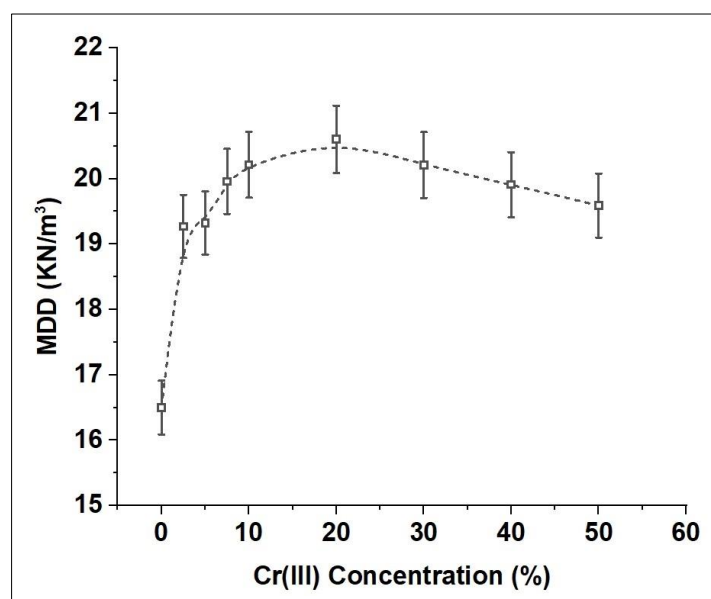


Figure 5. Variation of Maximum Dry Density with Cr(III) Concentration

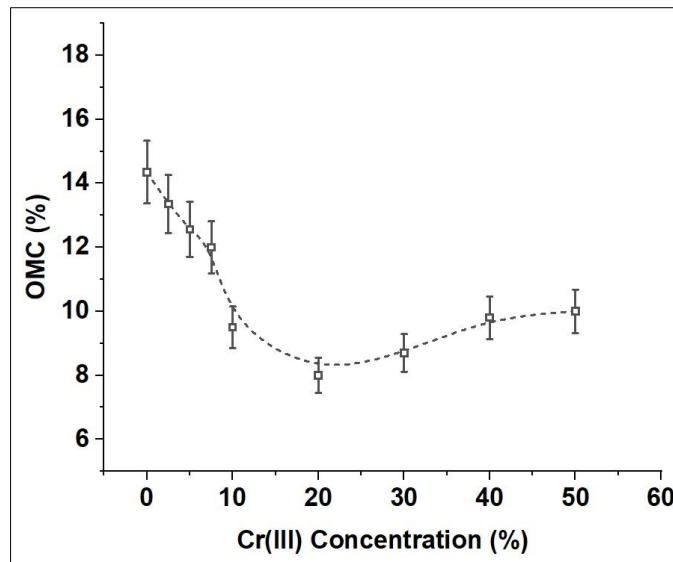


Figure 6. Variation of Optimum Moisture Content (OMC) with Cr(III) Concentration

OMC dramatically decreased up to the 20% addition of Cr(III) and increased steadily afterwards. The water absorption of Cr(III) tends to increase up to a 20% addition of Cr(III), after which the load is primarily resisted by the water molecules. The results were in line with the results of Atterberg’s limits due to the water absorption of Cr(III) at 20% concentration. The decline in OMC up to 20% Cr(III) addition and its subsequent increase also contrasts with previous studies [10]. It was highlighted that contaminants like heavy metals and industrial effluents caused a continuous rise in OMC due to increased water absorption. This emphasizes that with the subsequent emergence of contamination, Cr(III) primarily improves the particle packing. The additional Cr(III) may assist in building the hygroscopic compounds, leading to a higher OMC.

**3.3. Effect on Bulk Density**

The variation of bulk density with percentages of Cr(III) is presented in Figure 7. The results showed that the bulk density reached a plateau at 20% addition of Cr(III) and remained almost constant afterwards. This increase in the bulk density up to a 20% addition of Cr(III) is primarily because of the rearrangement of clayey soil and due to the higher density of Cr(III), as stated in section 3.2.

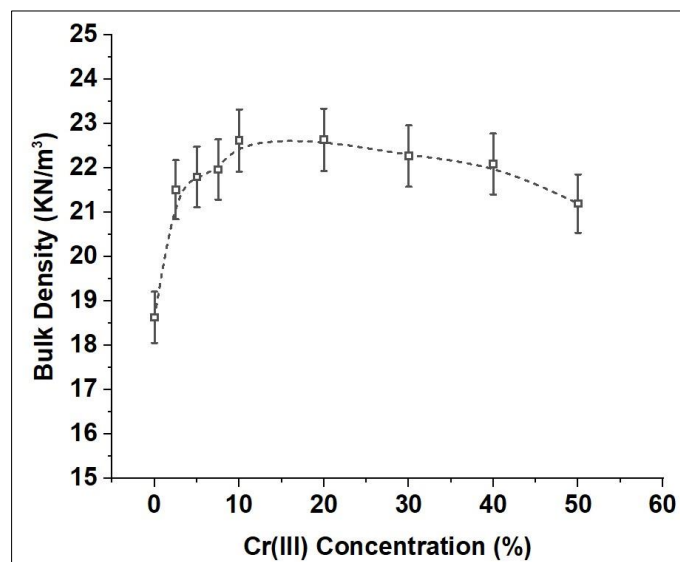


Figure 7. Variation of Bulk Density with Cr(III) Concentration

**3.4. Effect on Cohesion**

The variation of cohesion by the addition of Cr(III) is shown in Figure 8. The result highlighted an increase in cohesion up to a 20% addition of chromium trivalent Cr(III) and a decrease afterwards. The decrease in the cohesion value after the 20% addition of Cr(III) is because of several reasons such as: (i) an increase in soil ion concentrations

due to infiltration of Cr(III); (ii) damage in the soil's electric double-layer structure; (iii) thickening of the water surface for water absorption; and (iv) reduction in the cohesive force of the soil particles. The ion exchange capacity of Cr(III) ions in clay minerals, however, was higher than that of aluminum (III) and silicon (III) ions in clay minerals. As a result, these ions undergo substitution reactions with clay minerals and soluble salt cementing substances, destroying the soil skeleton structure and soluble salt cementing structure and making the soil sticky.

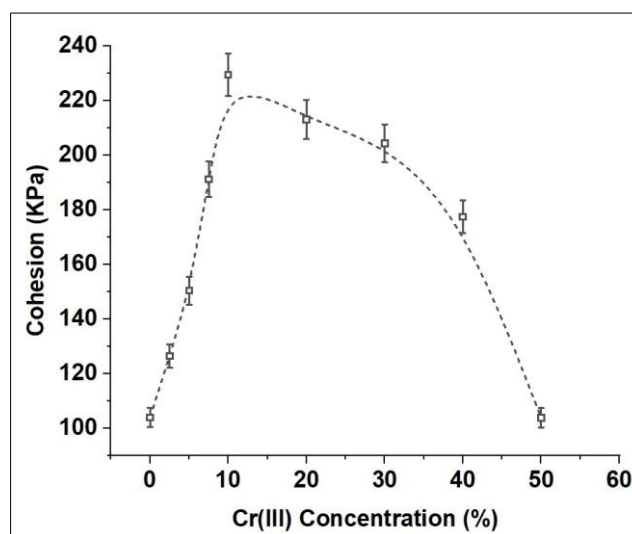


Figure 8. Variation of Cohesion with Cr(III) Concentration

The trend of the variation of cohesion with Cr(III) addition obtained in the present study is in agreement with previously published research studies. Research has shown that the cohesion of contaminated soil decreases as the concentrations of certain contaminants increase [31, 32]. The interaction between contamination and soil components disrupts the bonds between soil particles, leading to a reduction in cohesion. Furthermore, these chemical interactions alter the arrangement of minerals in the contaminated soil, leading to microstructural changes and a decrease in the specific surface area of the soil's particles [13].

### 3.5. Effect on Angle of Internal Friction

The variation in the angle of internal friction due to the addition of Cr(III) is shown in Figure 9. The result highlights that up to a 20% addition of Cr(III) increases the angle of internal friction, while a further addition then causes a decrease in it. The 20% addition of Cr(III) leads to infiltration of Cr(III) in the soil particles, causing damage to the soil structure and friction between the soil particles. These results contrast with the previous studies on Cr(VI) contamination, where the frictional angle generally remained in arbitration [13]. The distinctive behavior observed in the present study might be attributed to the unique interaction between Cr(III) and the clay minerals, which causes initial re-arrangement and densification of soil particles, unlike the dispersive effect of Cr(VI).

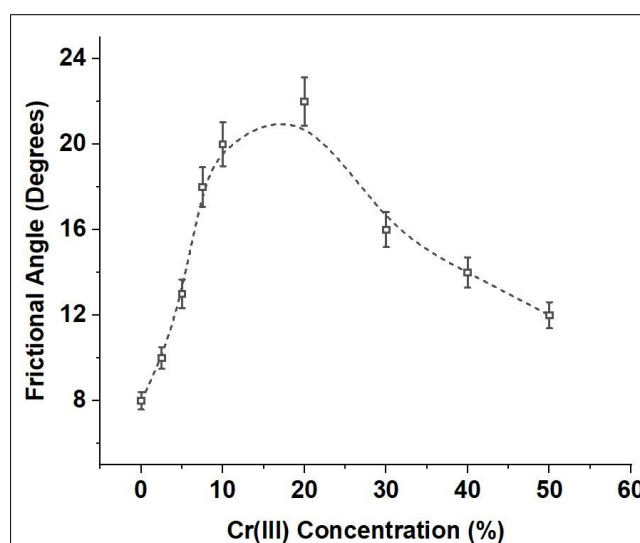


Figure 9. Variation of Angle of Internal Friction with Cr(III) Concentration

### 3.6. Effect on pH

The variation of the pH value of the soil with the addition of Cr(III) is presented in Figure 10. The pH value continuously decreased with the addition of Cr(III). As the Cr(III) concentration increased from 0 to 20%, the pH dropped from 8.2 to 4.7 due to the acidic nature of Cr(III). An aqueous solution of Cr(III) is considered to be an acidic medium material having a pH value of 3.50. The overall pH of contaminated soil samples was affected accordingly with the addition of Cr(III). Similar observations were highlighted in previous studies; however, increased Cr(III) affects only the levels of acidity through secondary processes [26]. This pH change is important in soil minerals and structure, as analyzed by XRD and SEM analyses. The original soil was basic, having a pH value of 8.2. The obtained results are in agreement with already published research studies [5, 13].

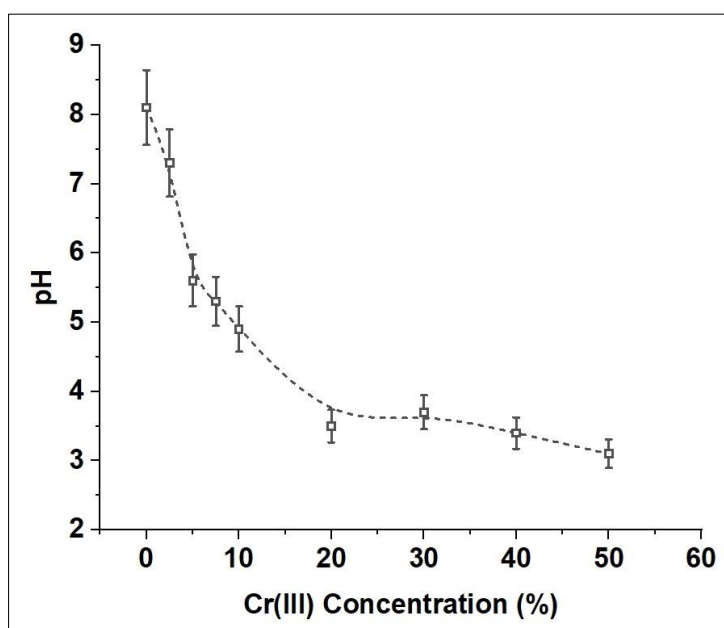


Figure 10. Variation of pH of soil with Cr(III) Concentration

### 3.7. Mineralogy and Structure of Contaminated Soil

The mineralogy of the soil with the addition of Cr(III) was examined by performing XRD tests, whereas the structure of the contaminated soil was studied by performing SEM analysis. The SEM analysis and XRD tests were performed considering five (05) cases, i.e., (i) pure soil, (ii) pure Cr(III), (iii) clayey soil with a 7.5% addition of Cr(III), (iv) clayey soil with a 10% addition of Cr(III), and (v) clayey soil with a 30% addition of Cr(III). The impact of Cr(III) addition on the soil structure investigated through SEM analysis is presented in Figure 11. The EDS results are presented in Table 3. The results highlighted that O, Si, and Ca were the dominant elements in pure soil, having weights of 47.92%, 17.6%, and 13.71%. However, the addition of Cr(III) reduced the weight of O. A relatively dense and strong bonded structure with packed particles and nominal void spaces is observed in the microstructure of the pure clayey soil, as presented in Figure 11-a. This indicates stable soil with adequate antiparticle forces.

On the contrary, crystalline morphology with irregular particle shapes was exhibited in the microstructure of pure Cr(III). Noteworthy alteration in the soil fabrics can be observed with the addition of Cr(III). The structure of the soil becomes more flocculated and aggregated at lower contamination levels, i.e., up to 20, as shown in Figures 11-c and 11-d. This alteration in the soil structure is primarily because of the exchange of cations and a decrease in the repulsive forces. Therefore, improved bonding and compact arrangement result, which aligns with the observed increase in strength characteristics and density of the soil. However, a higher contamination level leads to disordered soil structure with clear voids and breakage of aggregated clusters, as presented in Figure 11-e. Therefore, the interparticle bonds become weak, leading to lower values of cohesion and strength parameters. The observations recorded in the SEM analysis confirmed the dual effect of the Cr(III) addition in the soil, initially enhancing particle arrangement and later resulting in structural degradation.

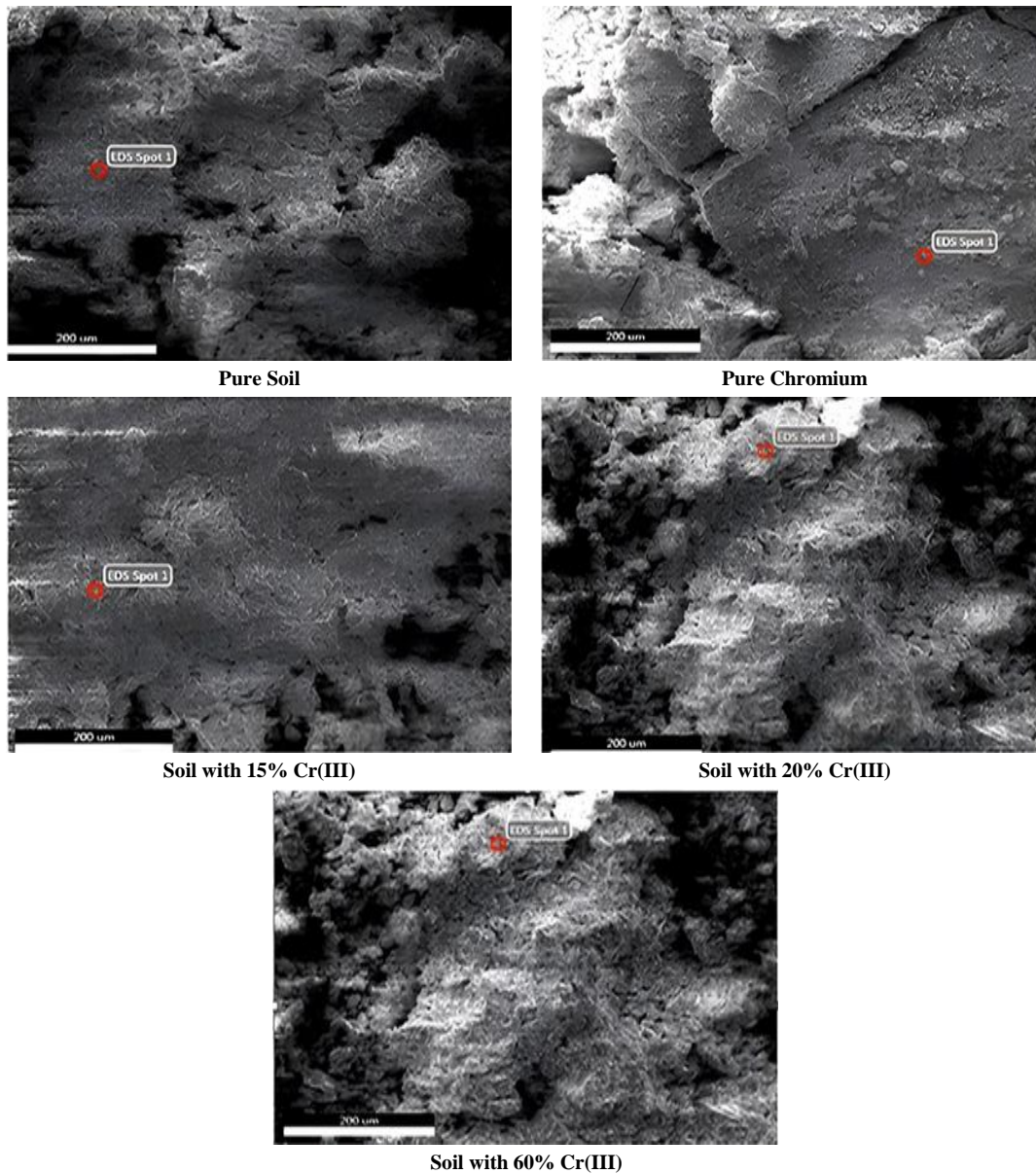
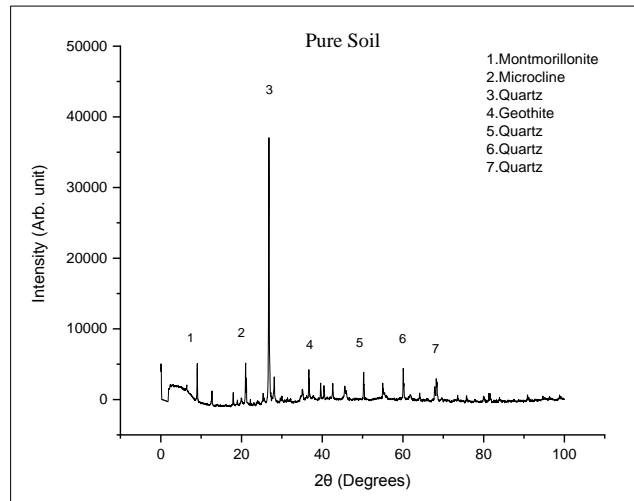


Figure 11. Results of SEM Analysis

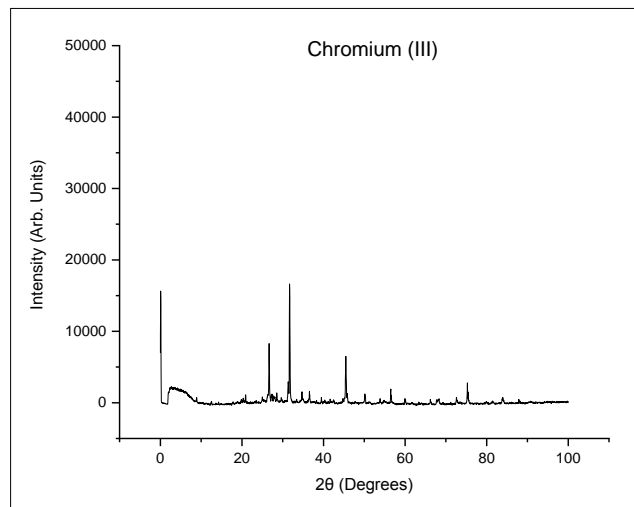
Table 3. EDS Results of Parent Soil, Pure Trivalent Chromium, Mixed Soil, and Trivalent Chromium

Element	Parent Soil			Pure Cr(III)			Soil with 15% Cr(III)			Soil with 20% Cr(III)			Soil with 60% Cr(III)		
	Weight (%)	Atomic (%)	Net. Int.	Weight (%)	Atomic (%)	Net. Int.	Weight (%)	Atomic (%)	Net. Int.	Weight (%)	Atomic (%)	Net. Int.	Weight (%)	Atomic (%)	Net. Int.
O	47.9	65.3	1054.2	10.1	17.4	105.5	31.9	48.5	340.2	33.3	53.1	675.8	28.2	45.0	395.8
Fe	5.6	2.2	34.9	-	-	-	-	-	-	-	-	-	-	-	-
Mg	1.1	1.0	39.2	-	-	-	1.72	1.7	23.4	2.2	2.3	90.7	1.2	1.3	36.5
Al	6.7	5.4	241.3	0.4	0.4	6.3	14.8	13.3	207.6	7.1	6.7	304.8	9.9	9.3	300.1
Si	17.7	13.7	632.6	-	-	-	27.7	23.9	366.6	12.1	10.9	527.3	25.8	23.5	760.4
P	5.9	4.2	161.9	-	-	-	-	-	-	-	-	-	-	-	-
K	1.3	0.7	24.8	-	-	-	4.7	2.9	33.4	1.5	1.0	34.5	3.1	2.0	46.9
Na	-	-	-	36.4	43.5	511.5	1.9	2.0	17.8	0.7	0.8	18.2	0.6	0.6	11.4
S	-	-	-	12.7	10.9	184.6	-	-	-	-	-	-	-	-	-
Cl	-	-	-	26.3	20.4	308.9	0.5	0.3	4.2	0.5	0.3	14.6	0.5	0.4	9.6
Cr	-	-	-	14.0	7.4	46.8	-	-	-	-	-	-	-	-	-
Fe	-	-	-	-	-	-	16.7	7.3	26.9	13.2	6.0	69.6	9.1	4.2	31.8
Ca	-	-	-	-	-	-	-	-	-	29.6	18.9	30.4	20.9	13.3	10.8
Ti	-	-	-	-	-	-	-	-	-	-	-	-	0.8	0.5	7.6

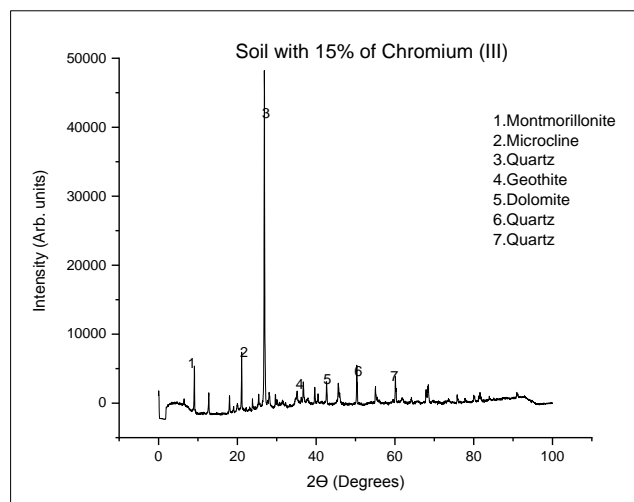
The XRD results are presented in Figure 12. It can be observed that Quartz was the dominant mineral in the pure clayey soil. Noteworthy modifications in the peak intensity and mineralogical composition are observed with the addition of Cr(III). At moderate contamination levels (up to 20% addition of Cr(III)), as shown in Figures 12-c and 12-d, an increase in the intensity of quartz peaks is evident, indicating improved compaction and reorientation of mineral structures. This observation correlates well with the increase in compaction and shear strength parameters observed with a 20% addition of Cr(III). The higher contamination level (up to 60%), as presented in Figure 12-e, yielded a lower peak intensity of quartz, suggesting evident disturbance in crystalline structure. This observation suggests that higher Cr(III) in the soil disrupts its mineralogical stability, leading to a reduction in its engineering properties.



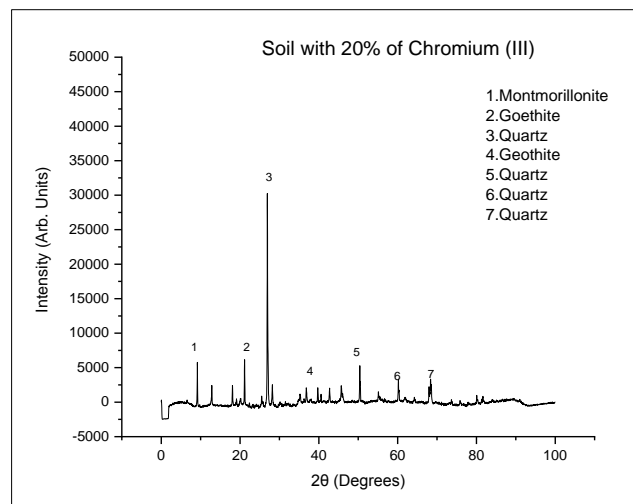
(a)



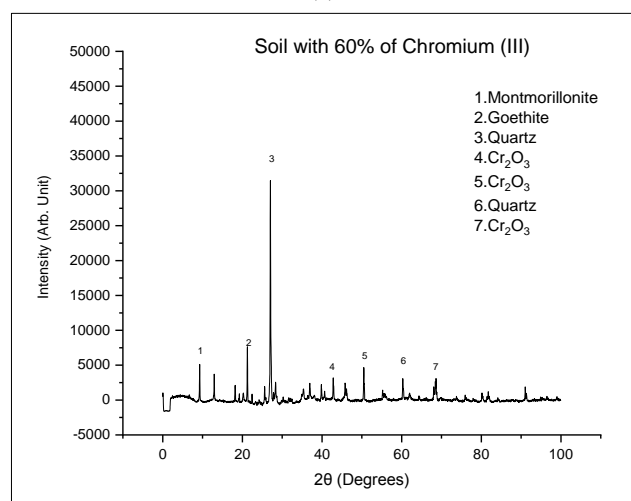
(b)



(c)



(d)



(e)

**Figure 12. Results of XRD analysis (a) pure soil, (b) Cr(III), (c) Soil with 15% Cr(III), (d) Soil with 20% Cr(III), and (e) Soil with 60% Cr(III)**

The result of the present study showed that the addition of Cr(III) in the soil significantly affects the geotechnical properties of clayey soil. The addition of Cr(III) altered soil structure, leading to the rearrangement of minerals in the clayey soil. Additionally, the water absorption of the soil tends to increase with the addition of Cr(III). Another notable effect of Cr(III) addition was damage to the soil's electric double-layer structure, increasing the thickness of the water layer, enhancing water absorption, and lowering the cohesive force of the soil particles.

The shear strength of the soil is primarily governed by density, cohesion, and angle of internal friction of the soil [33]. The decrease in the aforementioned parameters of the soil with the addition of contaminant ultimately affects its bearing capacity, which is the most important parameter used in construction projects such as buildings, bridges, roads, etc. For an effective and efficient design, the precise evaluation of bearing capacity and consideration of various factors affecting the soil's bearing capacity are vital for design engineers. Therefore, the present study provides useful insights for practice engineers working in the construction industry. Another application of the present study is for professionals working in environmental sciences and engineering, as the leather industry is facing significant challenges due to the disposal of untreated waste/contaminants in water or soil having detrimental effects. Therefore, it becomes vital to explore and implement state-of-the-art techniques to reduce the impacts of untreated waste/contaminants for a sustainable and eco-friendly environment.

It is noteworthy that soil samples in the present study were collected from a single industrial site. The observed trends obtained from the current study can be interpreted within the broad framework of fine-grained clayey contaminated soil. The impact of Cr(III) is mainly governed by the physicochemical mechanisms, such as exchange of cations and alteration in the diffuse double layer. Therefore, the general trend, i.e., initial enhancement in the strength characteristics of the soil followed by a decrease in the strength and compaction characteristics, may be applicable to

other clayey soils exhibiting similar mineralogical composition. However, the extent of these effects is expected to vary due to variation in mineralogy, plasticity index, and the capacity of exchange in cations. Highly active clays may exhibit pronounced physicochemical alteration as compared to less active clays. Similarly, soil having a different mineralogical composition will have a different response to Cr(III) contamination.

Equally important is to note that the present study investigates the soil behavior instantaneously after mixing, thereby illustrating short-term responses to Cr(III) contamination. The contamination-soil interaction may evolve over time due to ongoing physicochemical and mineralogical processes. The aging and curing may lead to further adsorption onto clay mineral surfaces, exchange of ions with native cations, etc. Resultantly, this may modify the diffuse double layer and inter-particle forces, leading to an increase in stiffness of the soil at the early phase of the curing. On the contrary, prolonged curing may impact the stability of the ponds and will modify the porous structure of the soil, leading to a reduction in the strength and an increase in permeability. The time-dependent microstructural rearrangement may have a significant impact on the long-term engineering properties due to alteration in particle orientation and void ratio. Therefore, short-term improvement in the geotechnical properties with moderate Cr(III) contamination may not represent the long-term behavior of the soil in the field.

Lastly, the shear strength characteristics were obtained by unconsolidated undrained (UU) tests, which simulate the effects of short-term loading with minimal pore water pressure dissipation. This method was adopted to study the instantaneous response of the soil contaminated with Cr(III), relevant to rapid or sudden load applications. However, in the field condition, where long-term loading effects need to be investigated, the consolidation and drainage may have a significant impact on the geotechnical properties of the soil. The prolonged presence of Cr(III) in the soil will affect the consolidation characteristics due to changes in the soil hydraulic conductivity and compressibility. Under such scenarios, consolidation undrained (CU) and consolidation drained (CD) must be conducted to examine the impact of Cr(III) contamination on the time-dependent consolidation behavior, drainage, and other geotechnical parameters.

#### 4. Variance and Statistical Evaluation

To evaluate the variability and reliability of the experimental data, one-way ANOVA, a statistical analysis technique, was carried out. In addition, a nonlinear regression analysis was performed to examine the relationship between chromium concentration and the measured geotechnical properties of the soil.

##### 4.1. Nonlinear Regression Analysis

The regression analysis yielded coefficients of determination ( $R^2$ ) of 0.8256 for cohesion, 0.8472 for angle of internal friction, 0.7634 for maximum dry density, 0.4477 for bulk density, 0.8262 for optimum moisture content, and 0.9044 for pH, respectively. These values indicate a generally strong correlation between chromium concentration and the investigated parameters, except for maximum dry density, which showed a weak relationship. The combined use of repeated measurements, error bars, and regression analysis provides a robust statistical validation of the experimental results and enhances the dependability of the findings presented in this study (see Figure 13).

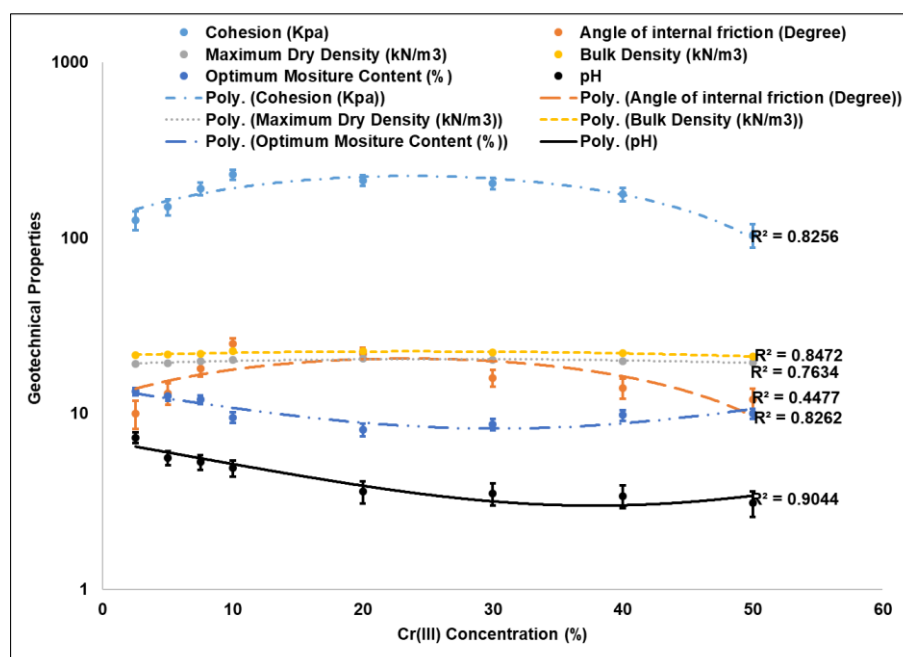


Figure 13. Results of Nonlinear Regression Analysis

## 4.2. Analysis of Variance

In addition to nonlinear regression, a one-way ANOVA was performed for each geotechnical parameter to evaluate whether differences across chromium concentrations were statistically significant. The results show that pH exhibits a strong and statistically significant trend with chromium addition ( $R^2 = 0.735$ ,  $p = 0.0065$ ), while optimum moisture content shows a moderate but non-significant trend ( $R^2 = 0.337$ ,  $p = 0.132$ ). Cohesion, angle of internal friction, maximum dry density, and bulk density displayed weak correlations with chromium percentage ( $R^2 < 0.06$ ,  $p > 0.56$ ), indicating no statistically significant change across the tested chromium levels for these parameters under the current dataset.

**Table 4. Results of One-Way ANOVA**

Parameter	R <sup>2</sup>	p-value	Interpretation (p < 0.05 = significant)
Angle	0.039	0.638	No significant trend
MDD	0.03	0.684	No significant trend
Bulk Density	0.048	0.6	No significant trend
OMC	0.337	0.132	Moderate trend but not significant
pH	0.735	0.0065	Strong, statistically significant trend

## 5. Conclusion

The present study aimed to investigate the impact of trivalent chromium (Cr(III)) contamination on the geotechnical, physicochemical, and microstructural properties of fine-grained clayey soil through a detailed experimental program. The results highlighted significant alterations in both index and engineering properties of the soil with the addition of Cr(III). Soil contaminated with Cr(III) showed improved performance, with maximum dry density, cohesion, and angle of internal friction increasing up to a 20% addition of Cr(III) by weight. This improvement is primarily attributed to cation exchange and the reduction in double-layer thickness, which leads to densification of soil particles. However, further increases in contamination level (above 20%) weakened the soil strength and compaction properties due to disruption of the soil fabric and reduced interparticle forces. A consistent decrease in pH of the contaminated soil was also observed, confirming the acidic nature of Cr(III).

Microstructural and mineralogical analyses further support these findings. SEM analysis revealed a transition from a dense, aggregated structure at lower contamination levels to a more porous structure at higher contamination levels. Furthermore, XRD analysis confirmed that quartz remained the dominant mineral phase, with peak intensities increasing up to 20% Cr(III) addition and decreasing thereafter, indicating a shift from stable to unstable mineral arrangements. These findings establish a clear relationship between chromium contamination, soil structure, and geotechnical characteristics. The study provides important insights into the dual role of Cr(III) contamination in modifying soil properties and highlights the importance of careful evaluation in geotechnical design, particularly in industrial regions where untreated waste disposal may affect soil stability.

### 5.1. Recommendations

The present study focuses on the short-term impact of Cr(III) contamination on the geotechnical properties of fine-grained soil. The investigated properties were determined by mixing soil with Cr(III) based on dry weight, and the experiments were conducted immediately. It is recommended that future studies extend this work by mixing soil with Cr(III) in liquid form and allowing sufficient curing time to assess the long-term effects of contamination. In addition, the influence of Cr(III) under prolonged loading conditions should be examined through CU and CD tests to account for consolidation and drainage effects. It is also recommended to investigate the impact of other pollutants, such as industrial plastic waste powder, on the geotechnical properties of soil. Finally, future research may explore the effects of contaminants on soil compressibility and collapse potential.

As discussed, this study examines the effect of Cr(III) on soil geotechnical characteristics. It is important to note that the leather industry faces significant challenges, particularly in waste management and effluent treatment. Untreated waste disposal in water or soil can have detrimental environmental effects. The implementation of advanced Effluent Treatment Plants (ETPs) may provide a viable solution for achieving a sustainable and environmentally friendly system. Further studies focusing on the installation and performance monitoring of ETPs are therefore recommended.

## 6. Declarations

### 6.1. Author Contributions

Conceptualization, A.H.B. and S.A.S.; methodology, A.H.B. and M.J.Q.; validation, U.P.K., M.Q., and I.A.K.; formal analysis, S.A.S. and S.L.; investigation, U.P.K. and S.L.; resources, K.H.L. and E.J.L.; data curation, S.A.S. and M.Q.; writing—original draft preparation, A.H.B. and M.J.Q.; writing—review and editing, S.A.S.; visualization, M.Q. and I.A.K.; supervision, K.H.L.; project administration, K.H.L. and E.J.L.; funding acquisition, K.H.L. All authors have read and agreed to the published version of the manuscript

### 6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

### 6.3. Funding

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### 6.4. Conflicts of Interest

The authors declare no conflict of interest.

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